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Using Fuzzy Cognitive Maps to Integrate Energy Modeling and Stakeholder Networks in Urban Low-carbon Energy Planning#

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ABSTRACT

The planning of urban low-carbon energy transition needs to be supported by scientific methods. However, current methods cannot integrate energy and social systems well. Conceptual frameworks can overcome this by expanding the research scope and identifying inter-disciplinary relationships, but it lacks quantitative approaches. This paper proposes an urban low-carbon energy planning method, which uses Fuzzy Cognitive Maps (FCM) to quantitatively integrate energy modeling and stakeholder network maps (SNM) based on Energy systems-Sustainability-Governance-Operation (ESGO) Conceptual Framework. The method includes 5 steps: 1) Propose a Conceptual Framework to explain the interactions between energy and social systems; 2) Energy System Modeling; 3) Social System Modeling; 4) Construct FCM; 5) Multi-scenario Analysis. A case study on Shanxi Transition Comprehensive Reform Demonstration (STCRD) Zone is used to verify the method feasibility. The results indicate that: 1) The method is feasible by depicting the interactions between social relations and energy technology changes; 2) The case study implicates energy saving is preferable in order to achieve carbon emission targets. Stakeholders' inclination towards low-carbon emissions is inducive to economic growth. Plans need to repeatedly adjust resource allocation and control the transition rhythm according to actual situations while maintaining long-term goals.

Keywords: Urban Low-carbon Energy Planning, ESGO, Fuzzy Cognitive Mapping, stakeholder network, energy model

NONMENCLATURE

Abbreviations	
SNM	Stakeholders Network Map
FCM	Fuzzy Cognitive Map
ESGO	Energy Systems-Sustainability-Governance-Operation
STCRD Zone	Shanxi Transition Comprehensive Reform Demonstration Zone
Symbols	
TEC	Total Energy Consumption
AL	Activity Level
EI	Energy Intensity
ES	Energy Structure
TCE	Total Carbon Emission
CEF	Carbon Emission Factor

1. INTRODUCTION

Urban low-carbon energy transition is crucial to mitigate climate change but faces unprecedented complexities involving technological transformation and social reformation[1, 2]. It urgently requires a scientific method which can depict these complexities.

Currently, there are two main types of planning methods, including energy system methods and social system methods. Energy system methods, such as EnergyPlan[3] and LUT Energy System Transition model[4] etc., use energy models based on laws of physics to simulate the development of energy systems. This type of method focuses on the technical changes of the energy system, but neglects social reality and reduces plans' feasibility[5]. Social system methods, such as multi-level perspective[6] and stakeholders theory[7] etc., are based on theories of humanity and society. These methods focus on social interactions and changes, but lack physical descriptions of energy systems[8].

Current research tends to connect and incorporate theories between these two methods[9, 10], however, due to differences in basic principles, the two types of methods still cannot sufficiently integrate energy and social systems' models. A conceptual framework

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provides a mean to bridge these differences, as a guiding framework to identify inter-disciplinary relationships[11]. Commonly used conceptual frameworks are, for example, Story and Simulation[1] and Energy Scenario Evaluation[12]. However, these approaches are either too resource intensive or too ambiguous for common practices. ESGO Conceptual Framework[13, 14] has more clarity in explaining connections between systems, but it lacks a quantitative approach. FCM, as a method of system thinking for quantifying network relationships, could be a solution[15].

Therefore, this paper proposes an urban low-carbon energy planning method, which uses FCM to tightly integrate energy and social systems based on ESGO Conceptual Framework. The main contributions include 1) a feasible method for urban low-carbon energy planning which can depict interactions between energy systems and social systems. 2) Suggestions by a case study on STCRD Zone.

2. METHODOLOGY AND CASE STUDY

2.1 Methodology

The methodology is divided into 5 steps (Fig. 1), in the following a brief description of each step is provided:

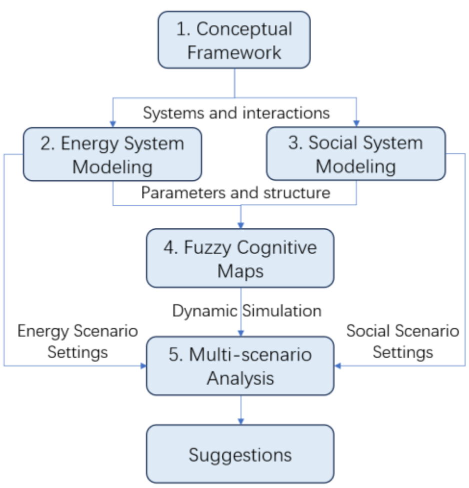

Fig. 1 Five-step method for urban low-carbon energy transition planning.

1) Conceptual Framework: to identify energy systems, social systems, and their interactions.

2) Energy System Modeling: to estimate emissions, and Energy Scenario Settings to decide technical transition pathways.

3) Social System Modeling: to simulate interactions between social bodies and convert this information into a network of causal relationships, and Social Scenario Settings to decide the preference of stakeholders and their coordination relationships.

4) FCM: to quantify casual relationships in social systems and integrate energy and social systems into one network.

5) Multi-scenario Analysis: to compare the coupled effect of energy and social scenarios on transition and identify the most effective scenario for transition.

2.2 Case Study

STCRD Zone is used as the case study. It was established in 2017 and consists of 8 national and provincial parks (divided into Taiyuan District and Jinzhong District) within Shanxi Province. Municipal governments of Taiyuan City and Jinzhong City and local management committee governances STCRD Zone together. STCRD Zone is the frontier of local economic development, low-carbon transition and has a large development potential. However, the current low-carbon development challenges are huge and there is a lack of strategic guidance.

2.3 Methods and Data Collection

2.3.1 ESGO Conceptual Framework

This paper draws on the main structure of ESGO Conceptual Framework proposed by Xiao et al.[14] and further adjusts it according to STCRD Zone's conditions. The Conceptual Framework for STCRD Zone (Fig. 2) indicates the process of urban low-carbon energy transition is affected by an innovation cycle. The key to promoting an energy transition is to induce the formation of the innovation cycle and accelerate its speed.

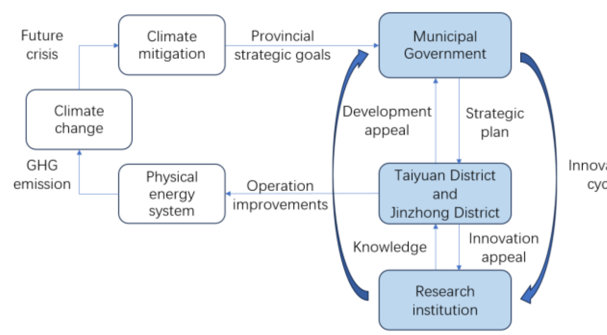

Fig. 2 Urban low-carbon energy transition conceptual framework for STCRD Zone. Interactions between blue components depict the innovation

The innovation cycle depicts the interactions between municipal government, energy system operators (Taiyuan and Jinzhong district in Fig. 2) and research institutions. These refer to the functions of institution, rather than particular intuition bodies.

Normally the innovation cycle begins with energy system operators, who put forward innovation requests for research institutions to reduce costs and increase productivity of the energy system. After scientific research, research institutions will feedback knowledge and technical solutions to energy system operators and induce innovations. However, in the context of energy transitions, local governments set strategic targets and policies to prompt or restrict energy system operators to focus on innovations supporting the energy transition process. This puts more pressure on the energy system operators and requires them to balance between profit and achieving low-carbon targets. If the targets are too high, energy system operators feedback the government to lower the targets and lessen the burden. This cycle will continue until an equilibrium is achieved where all stakeholders lower their goals to an acceptable level. The time required for the innovation cycle to reach equilibrium depends on the gap between each stakeholder's goal and the chosen transition pathway.

2.3.2 Top-Down Energy Model

Considering the limited energy data availability for STCRD Zone, this paper chooses a simple top-down energy model (Fig 3). Most of STCRD Zone's energy is imported and there are few energy conversion processes, only two combined heat and power enterprises. Therefore, the energy model only considers final energy consumption (including energy used for conversion). Energy types include coal, oil, natural gas, electricity, and heat. The accounting boundary of carbon emission is Scope 2. Local heat is mostly from geothermal energy, hence, emissions from heat consumption are neglected. This model divides energy consumption by districts.

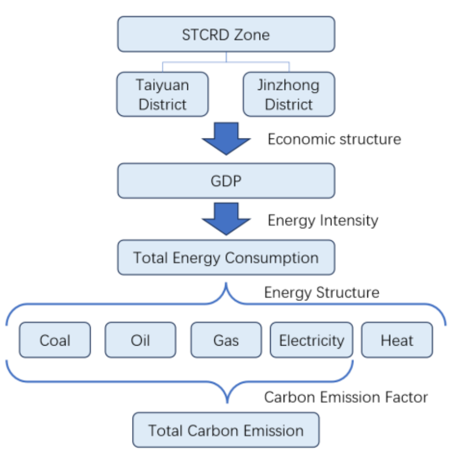

Fig. 3 Top-down energy model structure.

Total energy consumption is given by:

$$TEC = \sum_{i} \sum_{j} AL_{j,i} \times EI_{j,i} \times ES_{j,i} \quad (1)$$

TEC is the total energy consumption, $AL_{j,i}$ is the activity level, $EI_{j,i}$ is the energy intensity, $ES_{j,i}$ is the energy structure, the percentage of each energy type in the total energy consumption, i represents each energy type and j represents each district.

The total amount of carbon emissions is given by:

$$TCE = \sum_{i} \sum_{j} AL_{j,i} \times EI_{j,i} \times ES_{j,i} \times CEF_{i} \quad (2)$$

TCE is the total carbon emissions in the region, CEF_i is the carbon emission factor of each energy type.

Energy related data is collected from China Energy Statistical Yearbook, Research reports on STCRD Zone, public data from official websites[16, 17].

Technical transition pathways are reflected through Energy Scenario Settings. Scenarios project GDP and carbon emissions from 2021 to 2030. All scenarios are designed to control carbon emission to at least achieve the local carbon emission target based on current plans. There will be three energy scenarios: 1) Baseline scenario (E1), energy transition goes according to current plan until 2030; 2) Energy-saving scenario (E2), transition focuses on lowering energy intensity, keeping energy structure same as E1; 3) Electrification scenario (E3), transition focuses on electrification, energy intensity is adjusted to achieve carbon emission target.

2.3.3 Stakeholders Network Map

This paper chooses SNM because it simulates social systems with a network of causal relationships, making it easier to relate to the energy model. For detailed explanation of building SNM refer to [18]. In brief, SNM consists of concepts, edges, and signs, concepts are information from stakeholders related to the innovation cycle, these concepts are connected by edges depicting causal relationships, and the signs indicates positive or negative causality. Stakeholders' information is obtained through half-constructed interviews with multiple local government officials on low-carbon development, and review of public government documents on STCRD Zone.

SNM of the innovation cycle in STCRD Zone (Fig. 4) indicates there are two resistance and two encouragement feedbacks in this cycle. The two resistance feedbacks stem from the workload and difficulty of implementing energy-saving and low-carbon technologies. The difficultly depends on economic and carbon emission targets, if the targets are set too high, this leads to more energy consumption, and which means more technologies and engineering are needed to achieve emission targets. Thus, increasing the difficulty of energy saving and electrification, and hindering completion of the targets. The two encouragement feedbacks stem from the districts' need for development and overachieving of low-carbon targets. If the economic target is not achieved, the zone will be encouraged to fulfill its target; If the zone cannot achieve the economic target, which means less energy is consumed resulting in a decrease of carbon emissions, the low-carbon goals will be overachieved. That means the zone still has room for development, and the government is encouraged to promote economic growth.

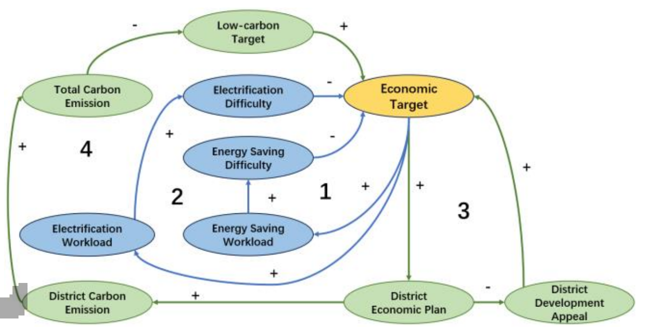

Fig. 4 SNM of innovation cycle in STCRD Zone. Loop 1&2 are resistance feedbacks, Loop 3&4 are encouragement feedbacks.

Actions of stakeholders to promote the transition are reflected through Social Scenario Settings. There will be 3 social scenarios: 1) Baseline scenario (S1), reflects the current situation and existing policies of stakeholders; 2) Low-carbon tendency scenario (S2), stakeholders are more inclined to low-carbon development; 3) Low-carbon coordination scenario (S3), stakeholders are inclined to low-carbon development, and resource coordination to support the corresponding technical transition pathways. Stakeholders' inclination refers to the awareness and motivations of the stakeholders to promote low-carbon transition. Resource coordination refers to the allocation of resource towards energy-saving measures or electrification, which results in decreasing difficulty.

2.3.4 Fuzzy Cognitive Map

This paper uses dynamic FCM[15], which focuses on the influences between each concepts. The term "dynamic" here refers to the propagation of changes caused by concepts, rather than changes over time. For detailed explanation of building FCM refer to [15]. In brief, FCM, consists of concepts, edges, and edge values. Concepts and edges are like those of SNM. Edge values represents the strength of influence of a concept to another, and their values, depending on the concepts, are determined by fuzzy logic based on stakeholders' information or energy model.

FCM of innovation cycle in STCRD Zone (Fig. 5) simulates the four feedback processes in SNM by corresponding loops. The logic of the two resistance loops is: 1) STCRD Zone devise a plan for transition, which requires a certain amount of workload for electrification and energy saving. 2) The workload determines the difficulty of electrification and energy saving. 3) Depending on the degree of difficulty, STCRD Zone might not be able to achieve the economic target. The logic of the two encouragement loops is: 1) STCRD Zone sets economic and low-carbon targets for each district. The districts would strive to achieve both targets. However, because of resistance loops they might not achieve 100% completion rate. 2) Failing to achieve its economic target prompts the district to make development appeals to achieve economic targets. 3) Being unable to achieve economic targets, will result is less energy consumption and carbon emissions, which leads to the overachievement of low-carbon target, this will induce the STCRD Zone to achieve economic targets.

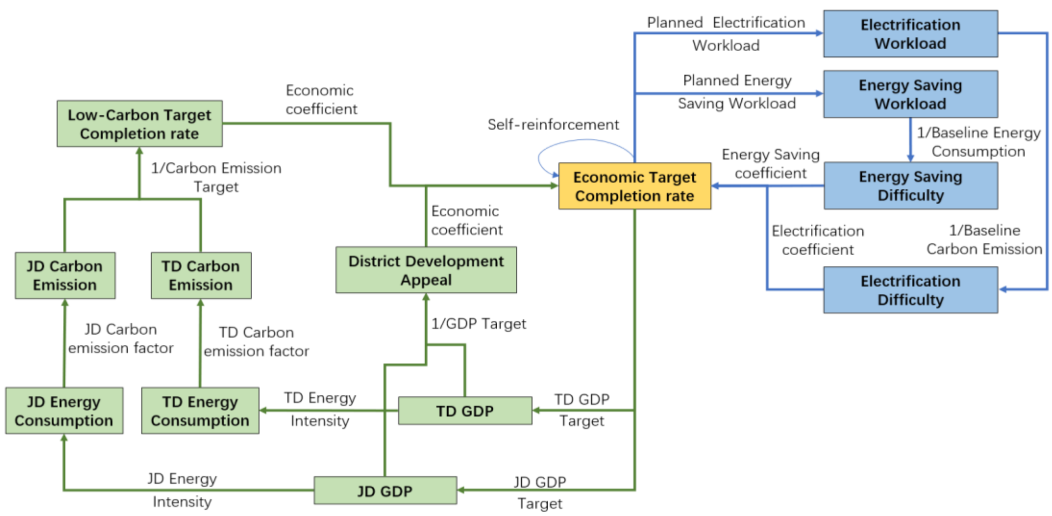

Fig. 5 FCM of innovation cycle in STCRD Zone. TD: Taiyuan District, JD: Jinzhong District. The green network corresponds to encouragement loops, and the blue network corresponds to resistance loops.

2.3.5 Multi-scenario Analysis

Multi-scenario Analysis uses dynamic simulation of FCM to simulate each coupled scenario and compares the results. Dynamic simulation is done by performing repeated matrix product of a state vector and a square adjacency matrix until the vector's values stabilize. State vector is an array of concept values that represents the whole system's influence on the concepts. Square adjacency matrix is a matrix of edge values that represents the capability of the system. For detailed explanation of dynamic simulation refer to [15]. Couple energy and social scenarios to result in 8 coupled scenarios (excluding E1-S3 scenario because it is the same as E1-S2). Each scenario setting determines a new set of edge values.

3. RESULTS AND DISCUSSIONS

E2-S3 scenario achieved the highest economic target completion rate (Fig. 6), which indicates energy-saving measures combined with stakeholders' inclination towards low-carbon development and resource coordination for energy-saving measures is the most effective pathway.

Comparing the energy scenarios, E2 scenarios achieve higher GDP and lower carbon emissions and carbon intensity than E3 scenarios (Table. 1), indicating that energy saving is more preferable than electrification in achieving carbon emission targets. This is because Shanxi Province relies heavily on coal-fired power plants to generate electricity, hence rapid electrification now will cause more carbon emissions, and to compensate for the extra emissions, E3 scenarios will have to accelerate in energy saving as well, this results in greater transition difficulty.

Comparing S1 and S2 scenarios reveals that stakeholders' inclination towards low-carbon emissions is inducive to economic growth. This can be viewed from two perspectives. Firstly, focusing on economic growth naturally leads to rapid growth in energy consumption and more emissions. However, this also means that stakeholders are less focused on low carbon development, which is not conducive to long term development, as the carbon emission target will become a limiting factor to economic growth. Secondly, if stakeholders pay more attention to low-carbon developments, it will lower the difficulties to promote the transition, and to achieve the carbon emission target more effectively. This in turn would be conducive to economic growth.

Comparing S2 and S3 scenarios reveals that resource coordination according to a single plan might not achieve desirable results. Under the E2 scenario, S3 achieves a higher economic target completion rate, which is expected since in E2-S3 resources are allocated for promoting energy saving, lowering its difficulty. But under the E3 scenario, S3 achieved lower results instead. This is because, although the difficulty of promoting electrification has decreased, the difficulty of energy saving has increased, since the E3 scenarios also need to promote energy saving to compensate for increasing carbon emissions from electrification. Hence, the net result is less beneficial. This elucidates the fact that plans

Table. 1 GDP and Carbon Emission in each scenario

Coupled Scenarios	GDP (Billion RMB)	Carbon Emission (Mt CO_2)	Carbon Intensity (ton CO_2/1000 RMB)
E1-S1	226.4	16.70	73.76
E1-S2	230.7	17.00	73.69
E2-S1	230.7	13.15	57.00
E2-S2	235.1	13.40	57.00
E2-S3	236.8	13.50	57.01
E3-S1	N/A	N/A	N/A
E3-S2	221.2	16.30	73.69
E3-S3	219.6	16.18	73.68

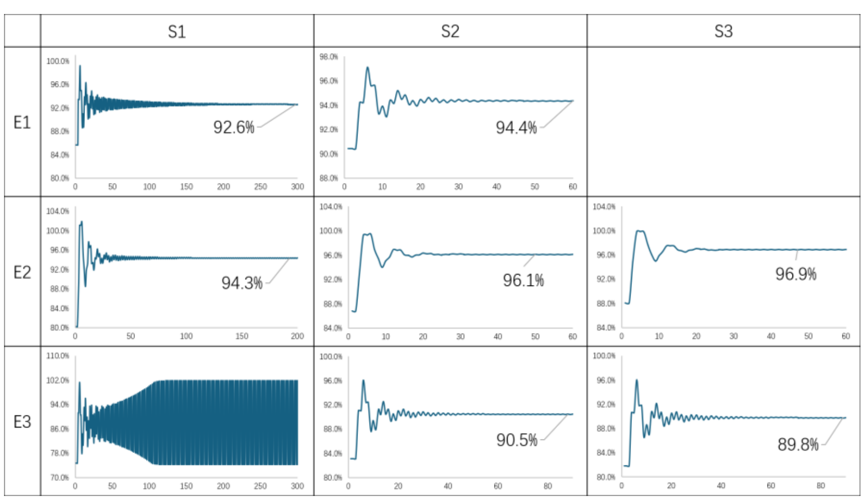

Fig. 6 Economic target completion rate each scenario.

require multiple sessions of communication between stakeholders to repeatedly adjust resource allocation and control the transition rhythm according to actual situations while maintaining long-term goals.

4. CONCLUSIONS

This paper proposed a method that uses FCM to quantitatively integrate energy modeling and SNM based on ESGO Conceptual Framework. The results indicate that this method is feasible. Modeling social systems with causal relationship networks allows information of social systems to be compatible with energy models. The method can depict the interaction mechanism between the main social relations and energy system changes during the transition process and put forward suggestions based on quantitative results for improvement.

The results further reveal that energy saving is more preferable than electrification in achieving carbon emission target. Stakeholders' inclination towards low-carbon emissions is inducive to economic growth. Plans need to repeatedly adjust resource allocation and control the transition rhythm according to actual situations while maintaining long-term goals.

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